Ground Based Long Baseline Interferometry (Keck, LBTI, PTI)

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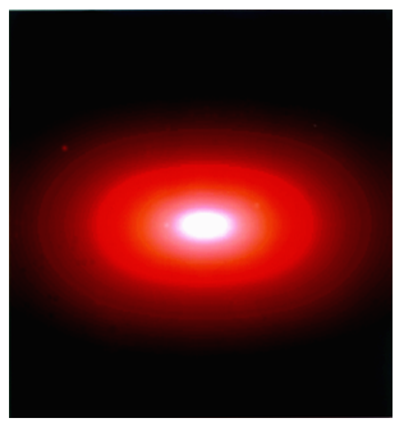
1. Introduction

Long baseline interferometry at infrared wavelengths with large telescopes offers milliarcsecond angular resolution with relatively high sensitivity. These instruments are therefore in a unique position to study objects at spatial scales not accessible through other means. Observations with near-infrared interferometers have already made substantial contributions to the fields of stellar astrophysics, star formation and even the central regions of active galactic nuclei. With the on-going development of high contrast techniques, these interferometers are also poised to make contributions to exo-planet science.

This white paper summarizes the status and future of several existing interferometry projects, the Keck Interferometer, the Large Binocular Telescope Interferometer and the Palomar Testbed Interferometer, as they relate to exo-planet research. First, a brief status of the individual projects is given. Then the contributions they can and are making to exo-planet science are discussed. Exozodiacal dust in exo-planetary systems limit TPF-C/I's ability to detect and measure the spectra of exo-Earths and will be studied by both KI and LBTI. Other science includes the study of the planet forming environment around nearby young stars and a search for planets in binary systems.



2. Interferometer current status and development plans

Keck Interferometer Status

The Keck Interferometer (KI) is the combination of the two 10-m Keck Telescopes on their 85-meter baseline and has a characteristic resolution of 5 milliarcseconds (mas) at 2 μm and 25 mas at 10 μm. The visibility amplitude mode is currently operational, while the nulling mode, dual-star and phase referencing capabilities are under development. KI is a NASA funded project jointly developed by the Jet Propulsion Laboratory, the W.M. Keck Observatory and the Michelson Science Center.

Visibility amplitude: This mode has been offered as a standard capability through the NASA, Caltech, UC, UH (and recently NOAO) TACs since April 2004 and is the only nationally accessible infrared interferometer in the U.S. It incorporates adaptive optics on both Keck telescopes, J- and H-band angle tracking, and H- and K-band fringe tracking with a limiting magnitude of K=10.3, making it the most sensitive near-infrared interferometer operating today. The W. M. Keck Observatory (WMKO) provides service observing, and the Michelson Science Center (MSC) provides observation planning, data infrastructure, and data calibration applications. KI data is publicly available after a proprietary period through the MSC.

Nulling interferometry mode: The nuller is concluding its development stage and entering its performance validation stage in preparation for an operations readiness review and Key Science call within the next year. It supports the key science measurement of exozodiacal dust around nearby stars in explicit support of TPF-I mission design as well as general exoplanet science.

The Nuller incorporates a sophisticated phase and angle tracking system using J-, H-, and K-band light to provide high-bandwidth pathlength and tilt control of the faint 10 μm signal. While required for KI to accommodate Earth rotation, and dry and wet atmospheric dispersion, such a system is similar to that required for platform stabilization of a space-based system. The Nuller also incorporates several novel measurement and calibration approaches to interleave tracking and science measurements, control systematic errors, and provide definitive set points for the control system to enable deep nulls.

First on-sky nulling measurements were made in 2005, with deep nulls demonstrated in August 2005. Subsequent work has focused on increasing performance and sensitivity. The current measured on-sky null leakage calibrates to a 1σ uncertainty of 0.6% for a science / calibrator pair, with a target value of 0.2% for a 2 Jy star, corresponding to ~100 times the exo-zodical dust in or own Solar System. At the target sensitivity, observations with the nuller are a factor of 10 times more sensitive than Spitzer observations at 10 μm to emission from dust in the habitable zone.

Future capabilities: An L-band beam combiner and camera will be installed in 2007 to enable 3.5 μm visibility measurements, which will be a unique capability among ground-based interferometers. An outgrowth of the KI project is a major addition, funded by NSF's Major Research Initiative program. This effort is described in more detail in the Keck Observatory white paper, a brief summary is given here. This effort, led by the Keck Observatory, implements phase referencing and dual star astrometry on KI. The first stage will allow fainter science objects to be observed by implementing a phase referencing mode that uses a bright nearby star to provide the piston correction; ultimately the limit should be K ~ 15 mag. The last is to implement an astrometric capability with an accuracy of 30-100 microarcsecond (μas).

These improvements will enable a broad range of science from the galactic center to AGN to exo-planets. While observations of transits and microlensing events may yield a limited number of planetary mass estimates for rare edge-on systems, astrometry remains the only practical method to determine accurate masses for a significant number of exoplanets, particularly for the nearby systems which are the likely candidates for future planet characterization observations.

Because astrometry measures an orthogonal dimension of motion, even astrometry from a single baseline can yield inclinations when combined with radial velocity measurements. With upgrade-enabled astrometric capability, astrometric signatures of Jupiter-mass planets can easily be measured (e.g., Eisner & Kulkarni 2001), enabling planetary mass measurements for about 60 exoplanets at a SNR of > 10 (assuming ten measurements with 100 μas). This large number of masses measured with 10% accuracy will allow investigation of correlations between planet mass and other orbital properties, such as the mass–eccentricity relation predicted by Chiang et al.'s (2002) divergent migration scenario.

Large Binocular Telescope Interferometer Status

The Large Binocular Telescope Interferometer (LBTI) project leverages the optimized infrared capability and spatial resolution of the common mount 2x8.4 m Large Binocular Telescope currently being completed on Mount Graham, Arizona. LBTI is a NASA funded project managed through the JPL Navigator program. Technical implementation of the project is being carried out at the University of Arizona, a partner in the LBT project. The LBT is currently operational as individual telescopes. Interferometric commissioning will begin in 2008. The LBTI is currently being fabricated and assembled at Steward Observatory in Tucson, Arizona. Acceptance testing of LBTI will take place in summer 2008. The instrument will then be shipped to LBTI, reassembled and integrated with the telescope. The commissioning of LBTI is scheduled to take place in 2009 which will enable the beginning of science operations in 2010.

Nulling mode: Nulling can be achieved to a deep level with the LBTI enabled by its relatively modest baseline of 14.4 m. This allows detection of dust as close as 0.7 AU for a star at 10 pc while still allowing for minimal null leakage due to the size of star. The detection level enabled by both the good infrared performance and deep nulling capable with the LBTI is equivalent to a dust disk 3-10 times the zodiacal dust in our own Solar System.

Palomar Testbed Interferometer Status

The Palomar Testbed Interferometer (PTI) was developed as a hardware, software and operational testbed for the Keck Interferometer and is currently maintained for science operations by the MSC on behalf of the PTI collaboration. It consists of three 40-cm apertures which can be combined pairwise on baselines of 85 to 110 meters and demonstrated the first dual star narrow angle astrometry. The PTI collaboration consists of scientists at Caltech, JPL, MIT, UC Berkeley and New Mexico Tech and has been the basis of many PhD theses. Although PTI's sensitivity is limited, it continues to serve as a valuable venue for technical development, such as the very narrow angle astrometry described below and still makes valuable scientific contributions.

3. Contributions to exo-planet science

Exo-zodiacal dust

In our own solar system, widespread dust grains are found in several regions, among them the zodiacal dust belt within a few AU of the Sun, and the Kuiper belt at distances greater than a few tens of AU from the Sun. Cold dust located in analogs of our solar system's Kuiper belt are now being detected around an increasing number of nearby stars, but detections of the inner exo-zodiacal dust remains more problematical, both because of the close angular proximity of such hot dust to the bright central stars, and the high contrast ratios implied by such tenuous dust features. Even for the few systems which are close enough be resolved at optical, mid-infrared or sub-millimeter wavelengths, direct imaging on scales corresponding to the habitable zone is not possible due either to the bright central star or the measurement resolution. Dust distribution models which can reproduce the observed spectral energy distributions are degenerate in dust location and temperature. At mid-infrared (MIR) wavelengths, the optical depth through our solar system's zodiacal dust disk emission is on the order of 10^{-7}, and its integrated emission is on the order of 5 x 10^{-5} of the Sun's flux. Since the latter is nearly two orders of magnitude brighter than the MIR (10 μm) emission of the Earth, successful exo-Earth imaging around nearby stars clearly calls for an understanding of the level of exo-zodiacal emission which is to be found around nearby main sequence stars. The characterization of such exo-zodiacal dust disks is thus a vital preliminary step on the road to the direct detection of terrestrial planets with planned space missions such as NASA's Terrestrial Planet Finder and ESA's Darwin missions.

Photometry can successfully detect slight excesses of dust emission around nearby stars, but only to the few-percent level, and recent Spitzer limits are typically at the level of many hundred zodi-equivalents. To get much beyond this level, high-contrast measurement techniques must be employed. One approach to the detection of close-in emission fainter than a few percent of the bright starlight is the suppression of starlight by means of e.g., coronagraphy or nulling

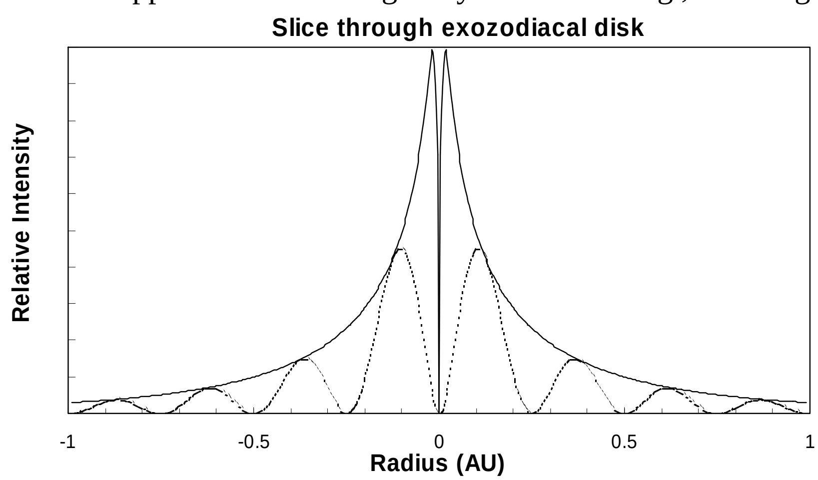


Figure 1. A slice through the exo-zodiacal dust emission from a solar system analog (solid), with the resultant transmission through the KIN fringe pattern superposed (dotted).

interferometry. Since most of the hot dust emission in our solar system arises at radii of order 0.1 – 1 AU (Fig. 1), MIR detection and characterization of such dust around stars out to a distance of about 10 pc at thermal infrared wavelengths requires interferometric baselines of order 10 – 100 m. At MIR wavelengths, the baseline of the KI thus couples most sensitively to the innermost, hottest dust emission regions of nearby stars while the LBTI baseline couples to dust around 1 AU for a solar-type star. Thus, the two facilities are complementary and taken together will allow a much better spatial characterization of the exo-zodical emission.

These high contract measurement techniques require sophisticated instrument design and control and somewhat different approaches are being pursued at KI and LBTI. In practice, a nulling instrument must remove both starlight and the thermal background emission in order to see faint circumstellar emission signatures. This is accomplished with the KI nuller by splitting the pupil of each Keck telescope into two halves, and implementing the nulling system as a four-aperture nuller, similar to the TPF baseline design. In detail, the starlight on the resultant pair of long baselines between the Keck telescopes is first nulled in a pair of very symmetric (Mach-Zehnder-type) nullers, after which a pair of standard Michelson beam combiners on the short-baselines are used to detect the residual circumstellar emission (which, being coherent, is seen as an a.c. signal, while the thermal background is at d.c.). Implementation of the KIN has already necessitated a number of innovative designs, and preliminary use of the instrument is now also providing a profitable venue for initial testing and use of faint signal detection strategies which will eventually be vital to TPF observational approaches. The good infrared performance of the LBT is enabled by its common mount design, sky baffled secondary mirrors, and the deformable element of its adaptive optics system built into the secondary mirror of each telescope. Since the instrument is located on the telescope mount, minimal optics are needed to achieve beam combination. The LBTI preserves the low background performance of the LBT through a completely croygenic beam combination.

Both KI and LBTI were designed and developed specifically to survey nearby stars for exo-zodical emission. KI will survey the brightest ~30 nearby solar-type stars for exo-zodical emission through an openly competed Key Science call. The LBTI will enable detection and characterization of the strength of zodiacal dust disks around approximately 60-80 nearby stars. Sixty nights will be dedicated to the nearby star survey and an additional one hundred nights is available to the astronomical community through NASA for related science enabled by the LBTI over eight years.

Circumstellar Disks

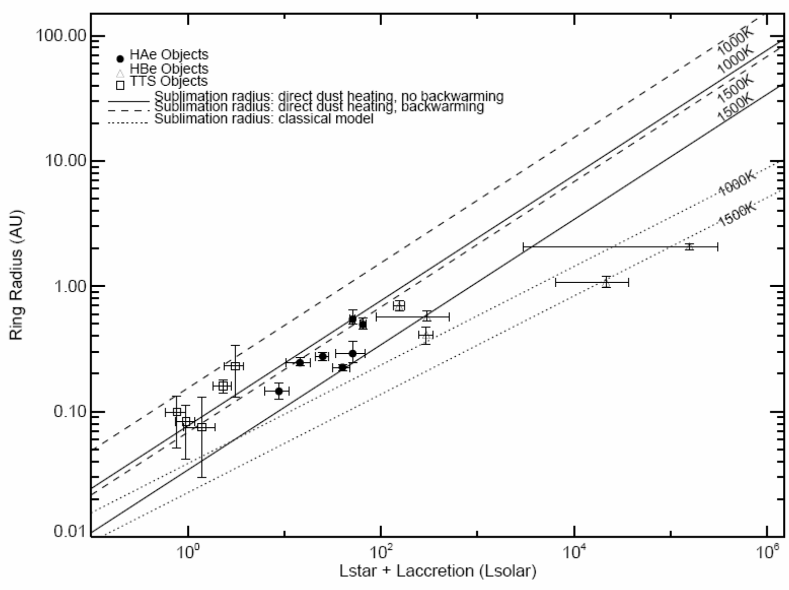


Figure 2. The relation between the measured near-infrared size and the total luminosity of young stars of all masses as measured by KI. Adapted from Monnier and Millan-Gabet et al 2002.

Near-infrared, long baseline interferometry is ideal for probing the inner (< few AU) regions of circumstellar disks around young stars. This material is the reservoir for any planet formation which may take place within the habitable zone. Many interferometers, including PTI and IOTA, have observed young stellar objects, but to date KI has made the most observations of YSO disks (Fig. 2) spanning a range of both age and mass from embedded to 10 Myr old T Tauri stars up to massive Herbig Be stars (Monnier et al. 2005, Akeson et al. 2005, Eisner et al. 2005). Initial observations of young T Tauris show that the inner dust radius is consistent with the dust sublimation radius and is larger than the orbits of the "Hot Jupiter" exo-planets. Observations of an older T Tauri star, TW Hya, provided evidence for dust close to the central star which may be generated by collisions between larger bodies in that system. More recent measurements have focused on measuring the gas in the inner disk using CO rotational lines. These observations demonstrate that the high sensitivity provided by the Keck apertures allows KI to probe T Tauris with a range of stellar and disk properties and a survey of these sources would characterize the physical properties of the dust and gas in the part of the circumstellar disk which will become the habitable zone for these stars.

Interferometry also contributes to the measurement of fundamental stellar properties (mass, luminosity, distance) of young stars, which are much less well determined than their main sequence counterparts. These measurements are crucial to provide constraints for stellar evolutionary tracks in the pre-main sequence regime. Boden et al. (2005, 2007) have used KI to measure the masses of T Tauri stars with ages from 3 to 10 Myr with better than 10% accuracy.

Planets Around Binary Stars, Palomar Testbed Interferometer

Current planet detection techniques generally concentrate on single stars; however, the majority of stars are in binary or higher multiple systems. So even though there are reasons to suspect that planets are rare in binary systems (e.g. Jang-Condell 2007), a more complete understanding of planet formation would include observational constraints from planet searches in binary systems. In particular, the relative prevalence of planets in single and binary stars can provide clues to the relative roles of gravitational instability and core accretion in planet formation. Studying systems that include relatively close pairs of stars (e.g. ~ 10—20 AU), where dynamic perturbations are the strongest, provides the most restrictive constraints of this type. These close pairs present an observational challenge; the planet-finding techniques (e.g. radial-velocity) successful for single star systems have limited precisions when applied to multiples.

The challenge of astrometric detections of planets in binaries comes from the small size of the reflex motions they cause to the host stars. Giant planets mass a factor of 10^3 less than stars, and are only stable in orbits sized of order 0.1 of the binary separation or smaller. Thus, one requires an astrometric precision of order 10^{-4} of the binary separation. To probe binaries close enough that dynamics might be important during formation (~20 AU), one must consider binaries separated by a few hundred mas, and the astrometry needs to be at the level of a few tens of μas. Such observations can be made with long baseline interferometers (Traub, 1996).

The dual-star astrometry method first demonstrated at PTI can be modified for use when the binaries are so close that the individual telescopes of an interferometer cannot resolve the pair (Lane and Muterspaugh, 2004). The interferometer itself over-resolves the binary and the stars' fringe packets are well separated in delay. The high spatial resolution then allows for precision relative astrometric measurements. In this mode, the small separation of the binary results in both components being in the field of view of a single interferometric beam combiner. The fringe positions are measured by modulating the instrumental delay with amplitude large enough to record both fringe packets. The observed separation of the fringe packets provides a measure of the separation of the stars in the sky.

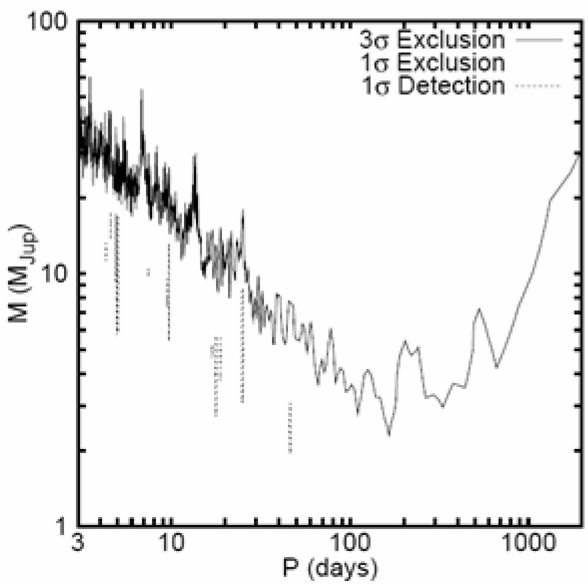


Figure : The excluded mass-period phase space for 13 Peg.

The demonstrated astrometric performance of this mode at PTI is at the level of 10-20 μas, the most precise optical astrometry program yet developed. This new observing mode forms the basis of the PHASES (Palomar High-precision Astrometric Search for Exoplanet Systems) program, which monitors 50 binary systems for low mass companions. It is an extremely sensitive search for Saturn- and Jupiter-mass planets in 6-18 month period orbits. Figure 3 shows the mass-period phase space in which PHASES observations show companions do not exist in face-on, circular orbits in the 13 Pegasi system.

The 13 Pegasi Mass-Period companion phase space shows PHASES observations can rule out tertiary objects as small as two Jupiter masses. A few mass-period combinations introduce slight improvements over the single-Keplerian model, but none of these are more significant than 1.7 σ, and are probably not astrophysical in origin. There is a long period cutoff in sensitivity due to the finite span of the observations. Similar detection limits have recently been published on other PHASES targets

Summary

After many years of development, large aperture infrared interferometry is now a reality and is contributing to many areas of astrophysics. In the field of exo-planet science, these facilities have a unique contribution to make in spatially resolving exo-zodiacal dust around nearby stars which will form the target lists of future missions to detect and characterize Earth-like planets. We recommend continued support for the technical development and for community access to this observing technique.

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